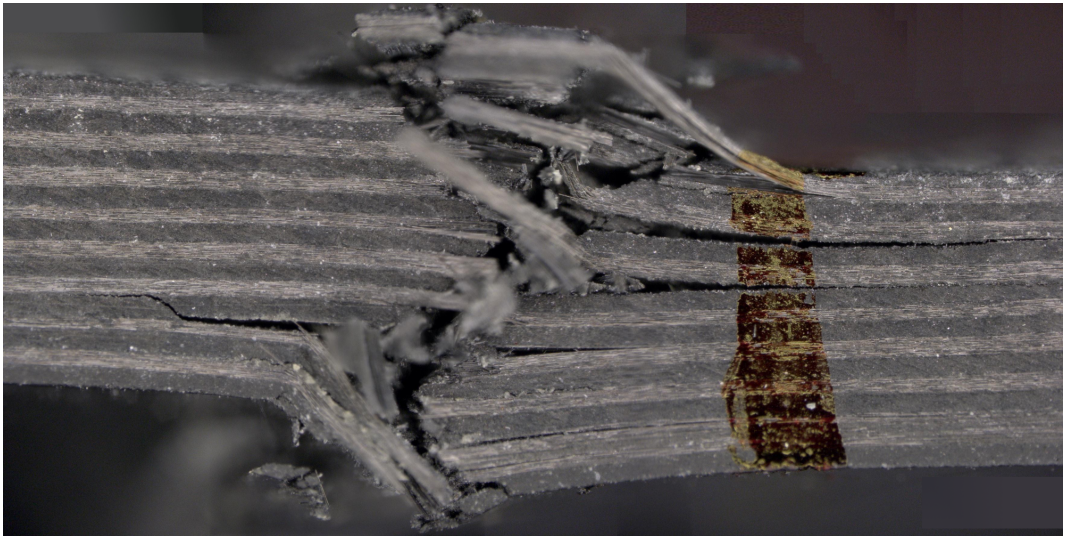
Virtual Parameter Determination for Damage Tolerance Analyses of Composite Structures

Martin Rädel et al.
DLR German Aerospace Center
Composite Structures and Adaptive Systems
Structural Mechanics
Braunschweig

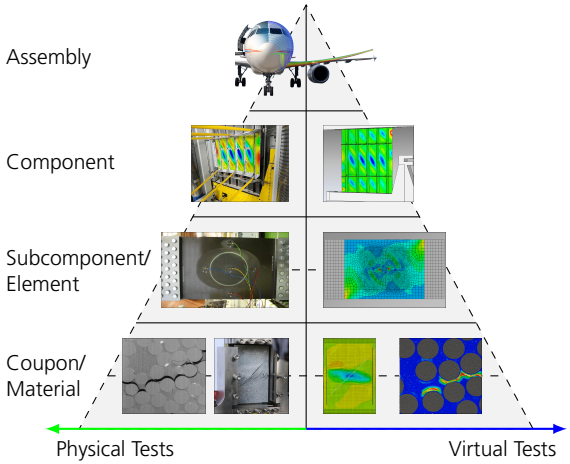
DLR FA Wissenschaftstag
24.10.2019

DLR



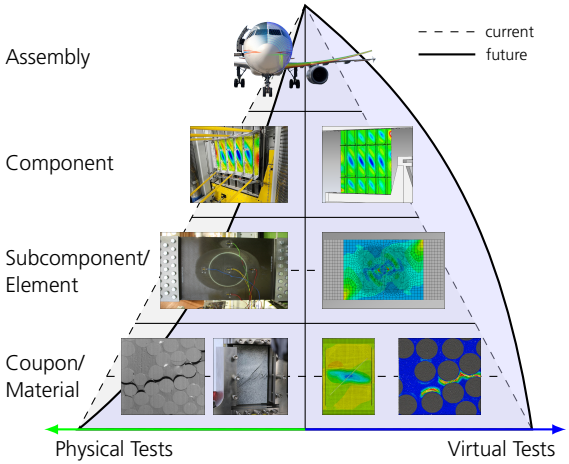
Challenges

- Task: Safe structures
  - Sizing complex structures
  - According regulations



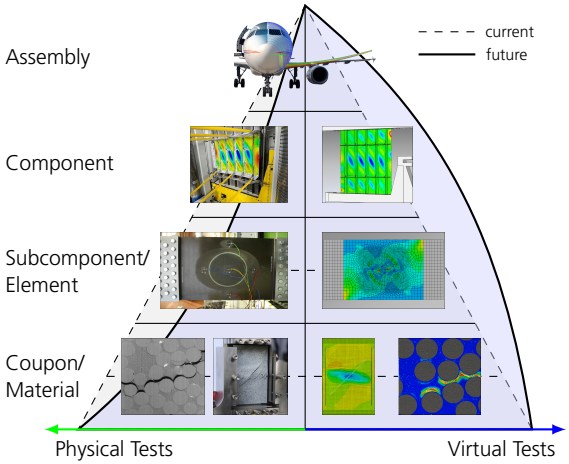
Challenges

- Task: Safe structures
  - Sizing complex structures
  - According regulations
- Goals:
  - Time-cost-risk reduction
  - Test determination & assessment
- By simulative prediction



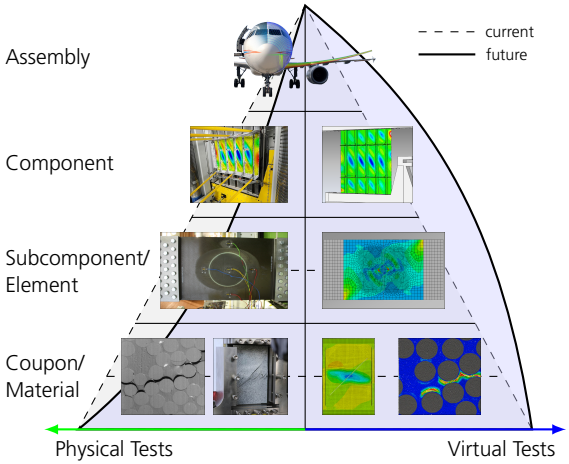
Challenges

- Task: Safe structures
  - Sizing complex structures
  - According regulations
- Goals:
  - Time-cost-risk reduction
  - Test determination & assessment
- By simulative prediction
- Requirement: Capture relevant phenomena



Challenges

- Task: Safe structures
  - Sizing complex structures
  - According regulations
- Goals:
  - Time-cost-risk reduction
  - Test determination & assessment
- By simulative prediction
- Requirement: Capture relevant phenomena
- Approach: Building Block



From phenomenon via modelling to simulation

- Sequence:
  - Test program
  - Understand phenomon
  - Enable modeling

From phenomenon via modelling to simulation

- Sequence:
  - Test program
  - Understand phenomon
  - Enable modeling

. . . the quality of a model is largely a function of its fitness for purpose.

A. Saltelli

From phenomenon via modelling to simulation

- Sequence:
  - Test program
  - Understand phenomon
  - Enable modeling
- Fitness for new
  - Material
  - Production technology
  - Topology
  - ...

. . . the quality of a model is largely a function of its fitness for purpose.

A. Saltelli

From phenomenon via modelling to simulation

- Sequence:
  - Test program
  - Understand phenomon
  - Enable modeling
- Fitness for new
  - Material
  - Production technology
  - Topology
  - ...
- Modeling still valid?

. . . the quality of a model is largely a function of its fitness for purpose.

A. Saltelli

From phenomenon via modelling to simulation

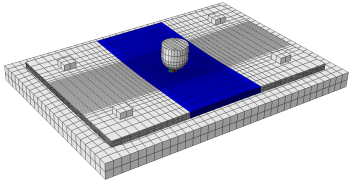
- Example: FEM
  Residual strength determination

From phenomenon via modelling to simulation

- Example: FEM
  Residual strength determination
- Configuration:
  - Monolithic CFRP
  - Compression after impact

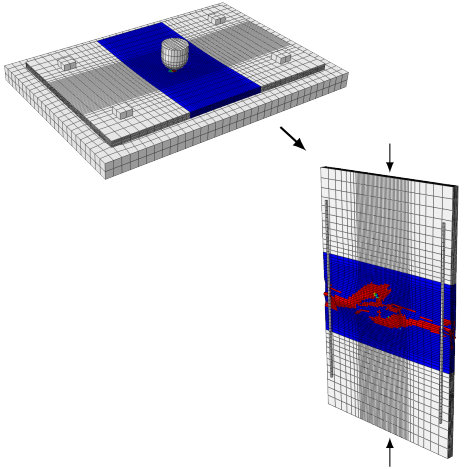
From phenomenon via modelling to simulation

- Example: FEM
  Residual strength determination
- Configuration:
  - Monolithic CFRP
  - Compression after impact
- Phases:
  - Impact



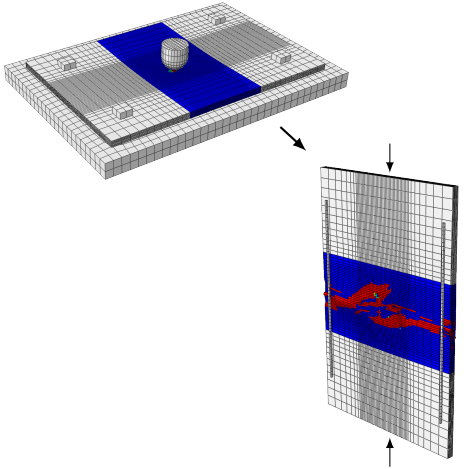
From phenomenon via modelling to simulation

- Example: FEM
  Residual strength determination
- Configuration:
  - Monolithic CFRP
  - Compression after impact
- Phases:
  - Impact
  - Compression damaged specimen
  - Comparison of strengths



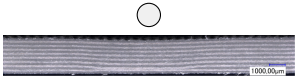
From phenomenon via modelling to simulation

- Example: FEM
  Residual strength determination
- Configuration:
  - Monolithic CFRP
  - Compression after impact
- Phases:
  - Impact
  - Compression damaged specimen
  - Comparison of strengths
- Aspects:
  - Stiffness
  - Damage
  - Stability



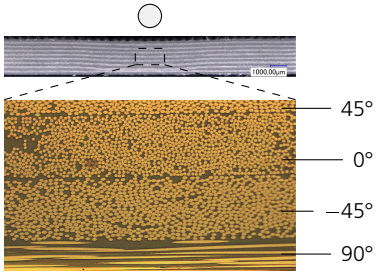
From phenomenon via modelling to simulation

- Closer look



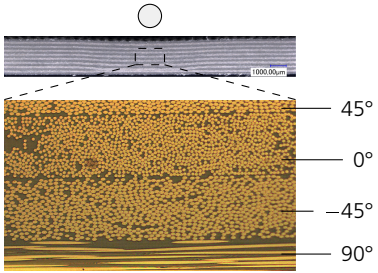
From phenomenon via modelling to simulation

- Closer look



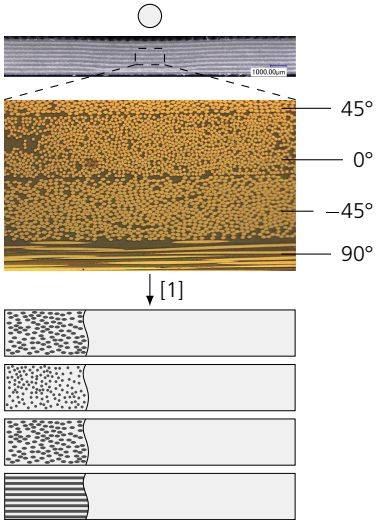
From phenomenon via modelling to simulation

- Closer look
- Damage phenomena
  - Fibre damage
  - Inter-fibre damage
  - Delamination



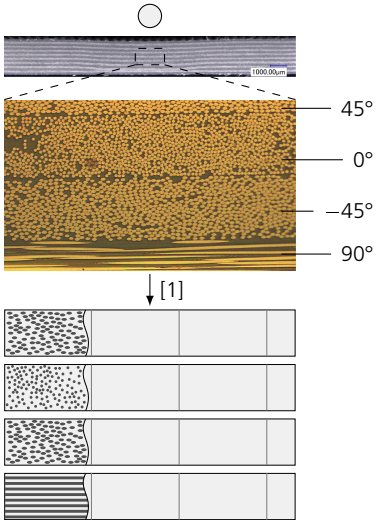
From phenomenon via modelling to simulation

- Closer look
- Damage phenomena
  - Fibre damage
  - Inter-fibre damage
  - Delamination
- Modeling



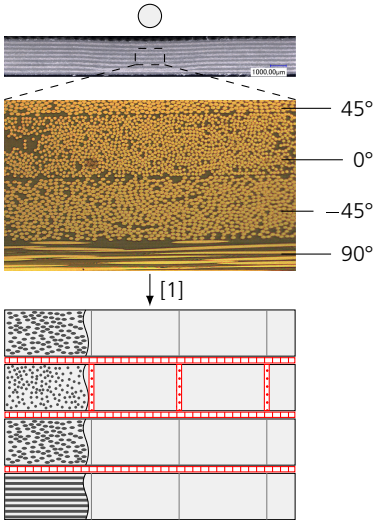
From phenomenon via modelling to simulation

- Closer look
- Damage phenomena
  - Fibre damage
  - Inter-fibre damage
  - Delamination
- Modeling
  - Discretization



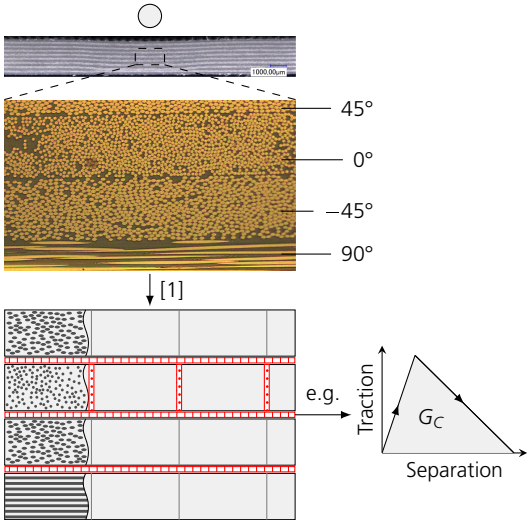
From phenomenon via modelling to simulation

- Closer look
- Damage phenomena
  - Fibre damage
  - Inter-fibre damage
  - Delamination
- Modeling
  - Discretization
  - Damage models:
    - interlaminar
    - intralaminar



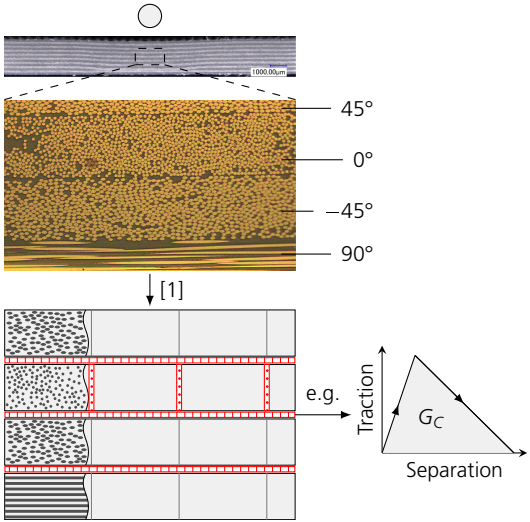
From phenomenon via modelling to simulation

- Closer look
- Damage phenomena
  - Fibre damage
  - Inter-fibre damage
  - Delamination
- Modeling
  - Discretization
  - Damage models:
    - interlaminar
    - intralaminar
  - E.g. cohesive zone models



From phenomenon via modelling to simulation

- Closer look
- Damage phenomena
  - Fibre damage
  - Inter-fibre damage
  - Delamination
- Modeling
  - Discretization
  - Damage models:
    - interlaminar
    - intralaminar
  - E.g. cohesive zone models
- Valid for different configuration?
- Why needed?



Damage - part of the problem or part of the solution?

- FEM, deformation **u**:
  - Can be very accurate & numerically efficiently
  - For undamaged domains
  - Assumptions?

Damage - part of the problem or part of the solution?

- FEM, deformation **u**:
  - Can be very accurate & numerically efficiently
  - For undamaged domains
  - Assumptions?

Continuum mechanics (CM) & FEM

- Assumptions [2]:
  - Continuous medium
  - **u** 2x continuously differentiable
  - Conservation equations satisfied
  - ...
- Momentum conservation: $\mathrm{div}(\boldsymbol{\sigma}) + \mathbf{b} = \rho\ddot{\mathbf{u}}$

Damage - part of the problem or part of the solution?

- FEM, deformation **u**:
  - Can be very accurate & numerically efficiently
  - For undamaged domains
  - Assumptions?
  - ↯: Not fulfilled @ discontinuities, e.g. cracks

Continuum mechanics (CM) & FEM

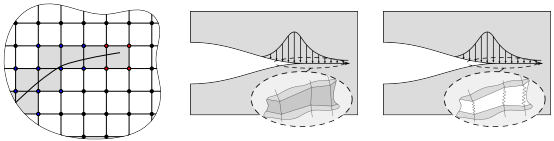
- Assumptions [2]:
  - Continuous medium ↯
  - **u** 2x continuously differentiable ↯
  - Conservation equations satisfied
  - ...
- Momentum conservation: $\mathrm{div}(\boldsymbol{\sigma}) + \mathbf{b} = \rho\ddot{\mathbf{u}}$

Damage - part of the problem or part of the solution?

- FEM, deformation **u**:
  - Can be very accurate & numerically efficiently
  - For undamaged domains
  - Assumptions?
  - ↯: Not fulfilled @ discontinuities, e.g. cracks
- Extensions:
  - XFEM, CZM, contact laws,. . .
  - Teach FEM reproduction phenomena

Continuum mechanics (CM) & FEM

- Assumptions [2]:
  - Continuous medium ↯
  - **u** 2x continuously differentiable ↯
  - Conservation equations satisfied
  - ...
- Momentum conservation: $\mathrm{div}(\boldsymbol{\sigma}) + \mathbf{b} = \rho\ddot{\mathbf{u}}$



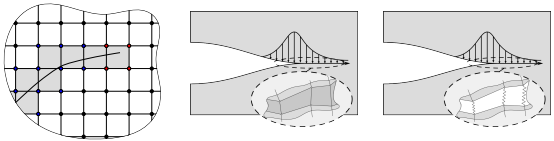
XFEM CZM Contact

Damage - part of the problem or part of the solution?

- FEM, deformation **u**:
  - Can be very accurate & numerically efficiently
  - For undamaged domains
  - Assumptions?
  - ↯: Not fulfilled @ discontinuities, e.g. cracks
- Extensions:
  - XFEM, CZM, contact laws,. . .
  - Teach FEM reproduction phenomena
  - Treat symptoms

Continuum mechanics (CM) & FEM

- Assumptions [2]:
  - Continuous medium ↯
  - **u** 2x continuously differentiable ↯
  - Conservation equations satisfied
  - ...
- Momentum conservation: $\mathrm{div}(\boldsymbol{\sigma}) + \mathbf{b} = \rho\ddot{\mathbf{u}}$



XFEM CZM Contact

Damage - part of the problem or part of the solution?

- More universal method?

Damage - part of the problem or part of the solution?

- More universal method?
- Peridynamics

Damage - part of the problem or part of the solution?

- More universal method?
- Peridynamics

Peridynamics (PD)

- Assumption: Conservation equations satisfied
- Momentum conservation:

$$\int_{\delta} (\underline{\mathbf{T}}(\mathbf{x}, t)\langle \mathbf{q} - \mathbf{x} \rangle - \underline{\mathbf{T}}(\mathbf{q}, t)\langle \mathbf{x} - \mathbf{q} \rangle)\, \mathrm{d}V_{\mathbf{q}} + \mathbf{b} = \rho \ddot{\mathbf{u}}$$

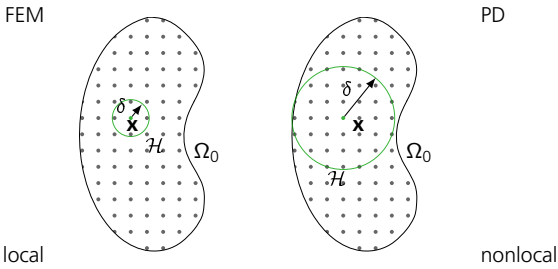
Damage - part of the problem or part of the solution?

- More universal method?
- Peridynamics
  - Integral formulation
  - Nonlocal

Peridynamics (PD)

- Assumption: Conservation equations satisfied
- Momentum conservation:

$$\int_{\delta} (\underline{\mathbf{T}}(\mathbf{x}, t)\langle \mathbf{q} - \mathbf{x} \rangle - \underline{\mathbf{T}}(\mathbf{q}, t)\langle \mathbf{x} - \mathbf{q} \rangle)\, \mathrm{d}V_{\mathbf{q}} + \mathbf{b} = \rho \ddot{\mathbf{u}}$$



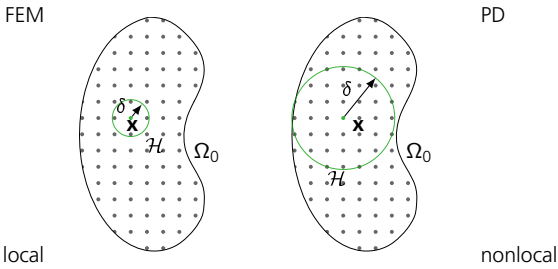
Damage - part of the problem or part of the solution?

- More universal method?
- Peridynamics
  - Integral formulation
  - Nonlocal
  - Cracks part of integration domain

Peridynamics (PD)

- Assumption: Conservation equations satisfied
- Momentum conservation:

$$\int_{\delta} (\underline{\mathbf{T}}(\mathbf{x}, t)\langle \mathbf{q} - \mathbf{x} \rangle - \underline{\mathbf{T}}(\mathbf{q}, t)\langle \mathbf{x} - \mathbf{q} \rangle)\, \mathrm{d}V_{\mathbf{q}} + \mathbf{b} = \rho \ddot{\mathbf{u}}$$



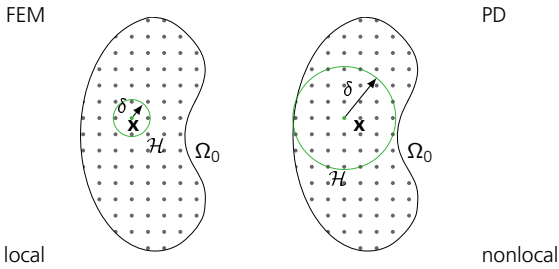
Damage - part of the problem or part of the solution?

- More universal method?
- Peridynamics
  - Integral formulation
  - Nonlocal
  - Cracks part of integration domain
  - CM special case of PD

Peridynamics (PD)

- Assumption: Conservation equations satisfied
- Momentum conservation:

$$\int_{\delta} (\underline{\mathbf{T}}(\mathbf{x}, t)\langle \mathbf{q} - \mathbf{x} \rangle - \underline{\mathbf{T}}(\mathbf{q}, t)\langle \mathbf{x} - \mathbf{q} \rangle)\, \mathrm{d}V_{\mathbf{q}} + \mathbf{b} = \rho \ddot{\mathbf{u}}$$



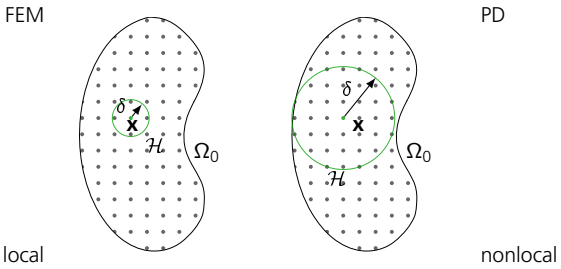
Damage - part of the problem or part of the solution?

- More universal method?
- Peridynamics
  - Integral formulation
  - Nonlocal
  - Cracks part of integration domain
  - CM special case of PD
  - Meshfree discretization
  - Peridigm [3]
  - Own extensions

Peridynamics (PD)

- Assumption: Conservation equations satisfied
- Momentum conservation:

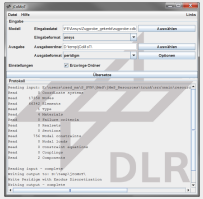
$$\int_{\delta} (\underline{\mathbf{T}}(\mathbf{x}, t)\langle \mathbf{q} - \mathbf{x} \rangle - \underline{\mathbf{T}}(\mathbf{q}, t)\langle \mathbf{x} - \mathbf{q} \rangle)\, \mathrm{d}V_{\mathbf{q}} + \mathbf{b} = \rho \ddot{\mathbf{u}}$$

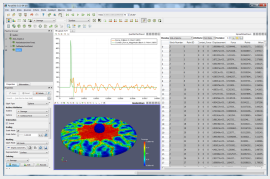


Simulation of phenomena with less modeling

Critical evaluation of peridynamics

Pre- & Postprocessing

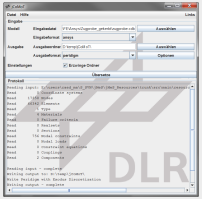


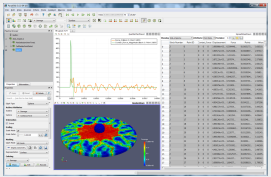


Simulation of phenomena with less modeling

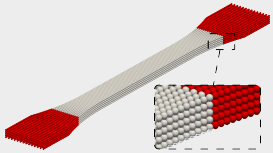
Critical evaluation of peridynamics

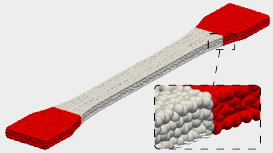
Pre- & Postprocessing





Discretization

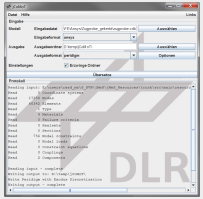




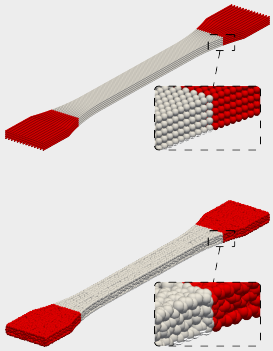
Simulation of phenomena with less modeling

Critical evaluation of peridynamics

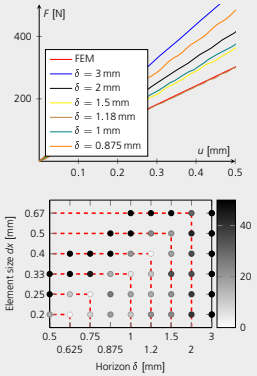
Pre- & Postprocessing



Discretization



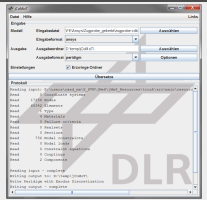
Convergence [4]

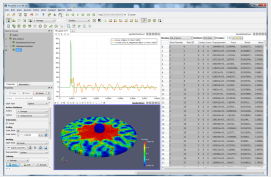


Simulation of phenomena with less modeling

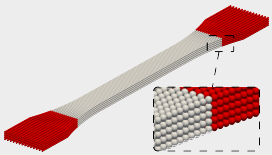
Critical evaluation of peridynamics

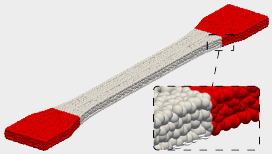
Pre- & Postprocessing



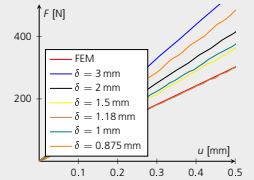


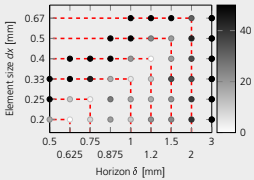
Discretization



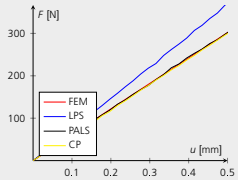


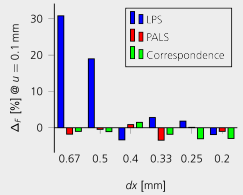
Convergence [4]





Formulations [5]



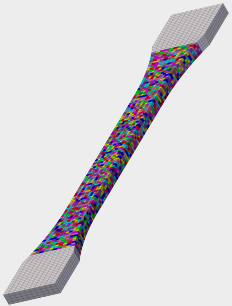


Simulation of phenomena with less modeling

Bottom-up

- Stiffness, Damage & Robustness

Base FE model

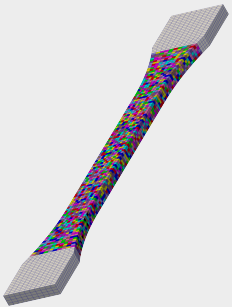


Simulation of phenomena with less modeling

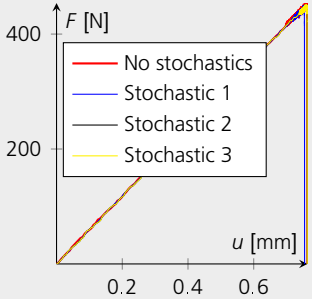
Bottom-up

- Stiffness, Damage & Robustness

Base FE model



Force-Displacement

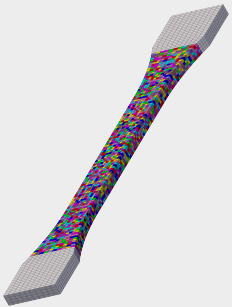


Simulation of phenomena with less modeling

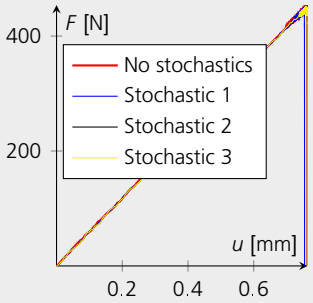
Bottom-up

- Stiffness, Damage & Robustness

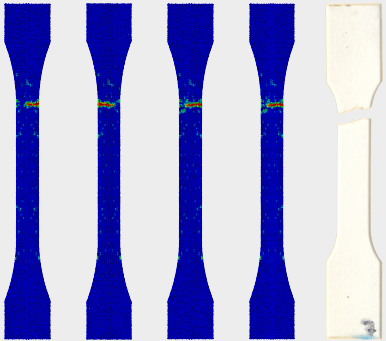
Base FE model



Force-Displacement



Failure patterns

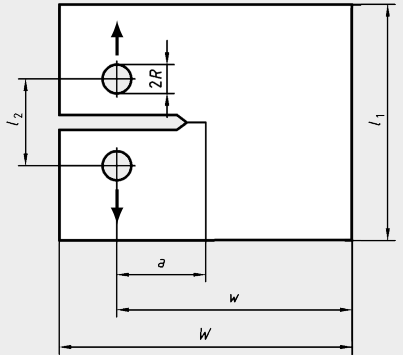


Simulation of phenomena with less modeling

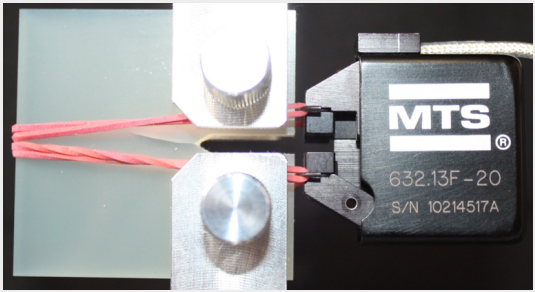
Bottom-up

- Determination G_C: CT specimen

ISO 13586:2000(E) [7]



Experiment

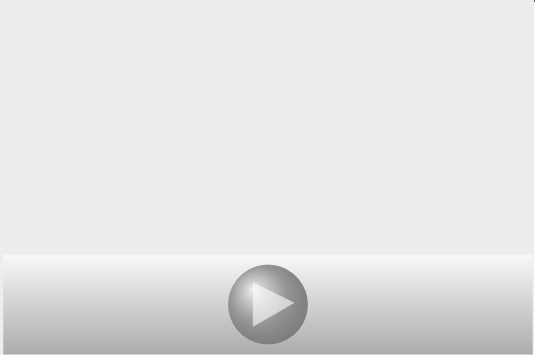


Simulation of phenomena with less modeling

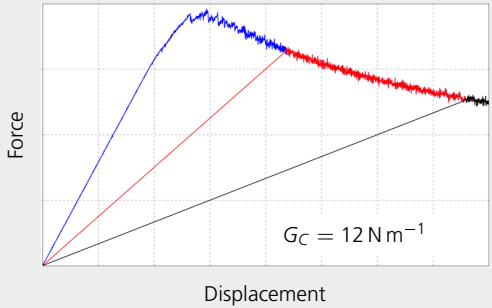
Bottom-up

- Determination G_C: CT specimen

Crack tip



Results

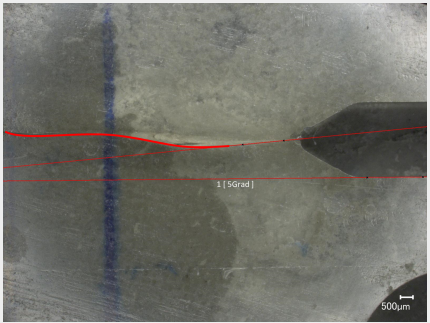


Simulation of phenomena with less modeling

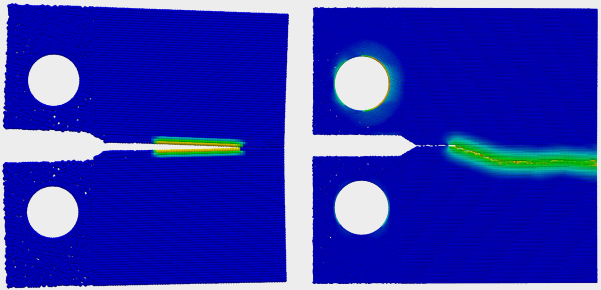
Bottom-up

- Determination G_C: CT specimen

Imperfections

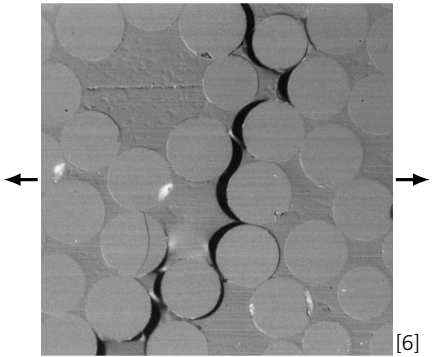


Results



Simulation of phenomena with less modeling
Complex problem

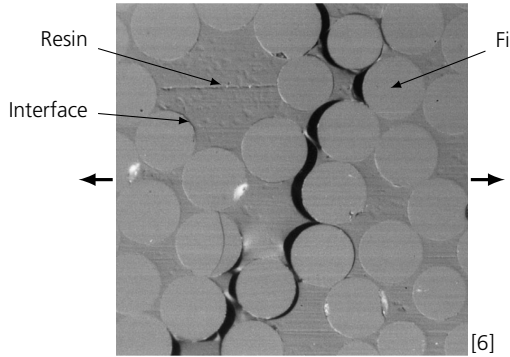
- Comparison modeling approaches damage for comparable significance
- [8]



[6]

Simulation of phenomena with less modeling
Complex problem

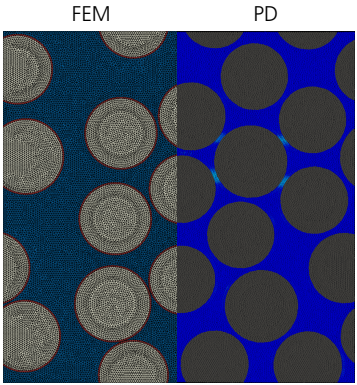
- Comparison modeling approaches damage for comparable significance
- [8]



[6]

Simulation of phenomena with less modeling
Complex problem

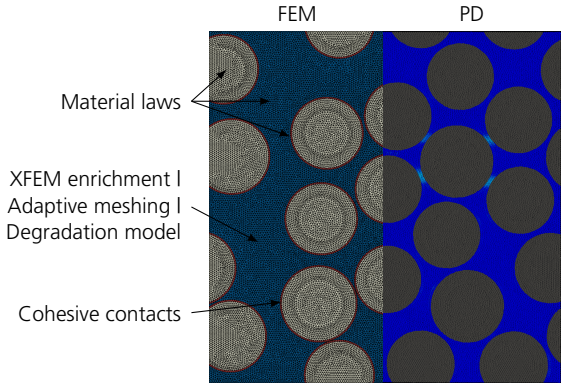
- Comparison modeling approaches damage for comparable significance
- [8]



Simulation of phenomena with less modeling

Complex problem

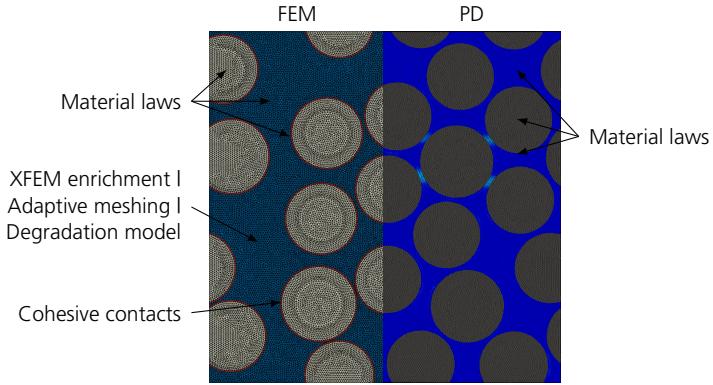
- Comparison modeling approaches damage for comparable significance
- [8]



Simulation of phenomena with less modeling

Complex problem

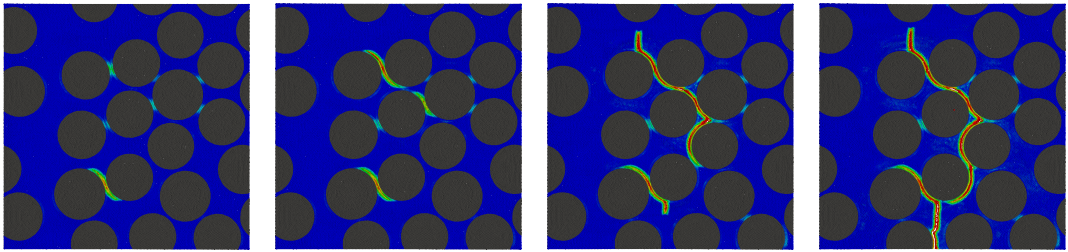
- Comparison modeling approaches damage for comparable significance
- [8]



Simulation of phenomena with less modeling

Complex problem

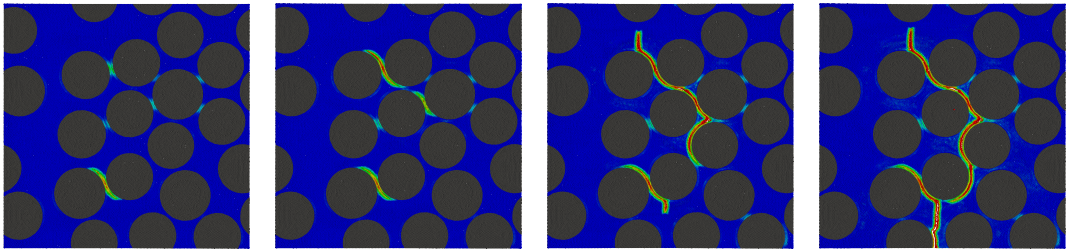
- Comparison modeling approaches damage for comparable significance
- [8], Peridynamic solution



Simulation of phenomena with less modeling

Complex problem

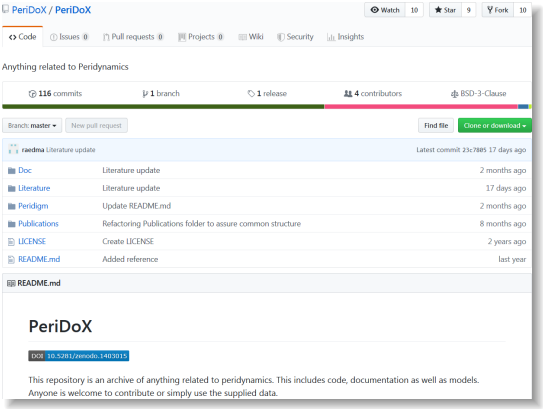
- Comparison modeling approaches damage for comparable significance
- [8], Peridynamic solution



- Reproduction physical phenomena, without additional modeling
- Damage can be part of the solution!

Conclusion & Outlook

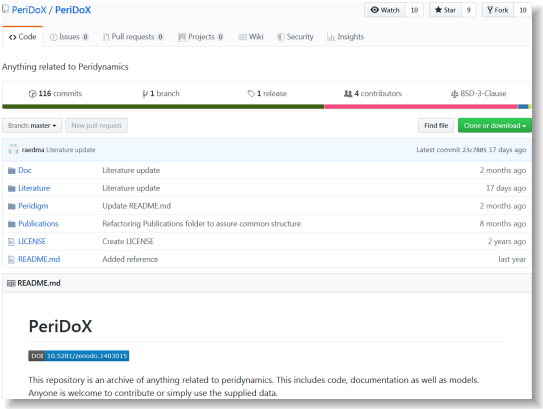
- Conclusion
  - More physics, less modeling
  - Enhanced verification of simulation-based modeling with FEM
  - Potential simulative predictions extended range applications



https://github.com/PeriDoX/PeriDoX

Conclusion & Outlook

- Conclusion
  - More physics, less modeling
  - Enhanced verification of simulation-based modeling with FEM
  - Potential simulative predictions extended range applications
- Outlook & research topics
  - Further quantitative validation
  - FE-PD coupling
- Cross-verification amongst partners, e.g. @ LSU, USA, Feb. 2020



https://github.com/PeriDoX/PeriDoX

Thank you for your attention.

Contact

Martin Rädel

German Aerospace Center
Institute of Composite Structures and Adaptive Systems
Department of Structural Mechanics

Lilienthalplatz 7
38108 Braunschweig
Germany

Cornelius-Edzard-Straße 15
28199 Bremen

☎ +49 (0)531 295–2048
+49 (0)531 295–2232
martin.raedel@dlr.de
www.dlr.de/fa

Bibliography I

[1] Raffael Bogenfeld, Janko Kreikemeier, and Tobias Wille. "Review and benchmark study on the analysis of low-velocity impact on composite laminates". In: *Engineering Failure Analysis* 86 (2018), pp. 72–99. ISSN: 1350-6307. DOI: 10.1016/j.engfailanal.2017.12.019.

[2] Florin Bobaru et al. *Handbook of Peridynamic Modeling*. Advances in Applied Mathematics. CRC Press, 2016. ISBN: 978-1315355948.

[3] Michael L. Parks et al. *Peridigm Users Guide v1.0.0*. Tech. Report SAND2012-7800. Sandia report. Albuquerque, New Mexico 87185 and Livermore, California 94550, USA, 2012.

[4] Martin Rädel, Christian Willberg, and Jochen Schmidt. "Effect of Discretization and Stochastic Material Distribution on Crack Initiation in Peridynamics". In: *14th U.S. National Congress on Computational Mechanics*. Montreal, Canada, July 2017.

[5] Martin Rädel et al. "Influence of probabilistic material distribution in peridynamics to the crack initiation". In: *6th ECCOMAS Thematic Conference on the Mechanical Response of Composites: COMPOSITES 2017*. Eindhoven, Netherlands, Sept. 2017.

Bibliography II

[6] Daniel Krause. "Micromechanics of the fatigue behaviour of polymers". DLR Report 2016-26. PhD Thesis. Technical University Braunschweig, 2016.

[7] ISO 13586:2000(E). *Plastics – Determination of fracture toughness – Linear elastic fracture mechanics (LEFM) approach*. Standard. Geneva, CH: International Organization for Standardization, Mar. 2000.

[8] Martin Rädel, Christian Willberg, and Daniel Krause. "Peridynamic analysis of fibre-matrix debond and matrix failure mechanisms in composites under transverse tensile load by an energy-based damage criterion". In: *Composites Part B: Engineering* 158 (2019), pp. 18–27. ISSN: 1359-8368. DOI: 10.1016/j.compositesb.2018.08.084.